CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
LHC-LQX-ES-0002 rev 1.0

CERN Div./Group or Supplier/Contractor Document No.
TD/FNAL/USA

EDMS Document No.

Date: 22 February 2001

Functional Specification

INNER TRIPLET QUADRUPOLE MQXB

Abstract

This specification establishes the functional requirements for the MQXB quadrupole magnets. Two of these elements form the Q2 inner triplet optical element at interaction regions 1, 2, 5 and 8. Since the elements are identical whether installed at the low luminosity or high luminosity interaction regions, the functional requirements to the magnet design are identical for all MQXB assemblies.

Prepared by :	*Reviewed by :*	*Approved by :*
J. Kerby **M. Lamm** FNAL Kerby@fnal.gov Lamm@fnal.gov	**J. Strait** FNAL Strait@fnal.gov	**[Name]** [division/institute] [electronic.mail]

History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
0.9	2000-09-29	All	Initial Submission
1.0	2001-02-22	10	Specify that pressure test is pneumatic.
		11	Change radiation dose numbers to correspond to 200 days per year operation, with corresponding change in expected lifetime.

Table of Contents

1. OVERVIEW

MQXB magnets are the quadrupole components which form the optical element Q2 in each inner triplet of the LHC, as described in the Inner Triplet Functional Specification [1]. The MQXB is the quadrupole magnetic element, including the coils and mechanical support pieces to a perimeter defined by the outer shell of the magnet, and the end plates of each magnet. MQXA assemblies are used in the Q1 and Q3 optical elements (Figure 1).

The completed 1.9K helium vessel, including both MQXB quadrupoles, the MCBX dipole corrector, and end domes, is named the LMQXC. The LMQXC, when joined with the Beam Position Monitor, and surrounded by cryostat shields, piping, and the vacuum vessel, is then the LQXC assembly, as installed in the tunnel of LHC.

The MQXB design and production is the responsibility of Fermilab. MQXA are the responsibility of KEK, and the corrector packages and beam position monitors are the responsibility of CERN. Fermilab is responsible for the design and assembly of the LMQX vessels, and the LQX cryostat assemblies. The beam position monitor mounting, and interconnect assembly are the responsibility of CERN.

This functional specification covers the MQXB only.

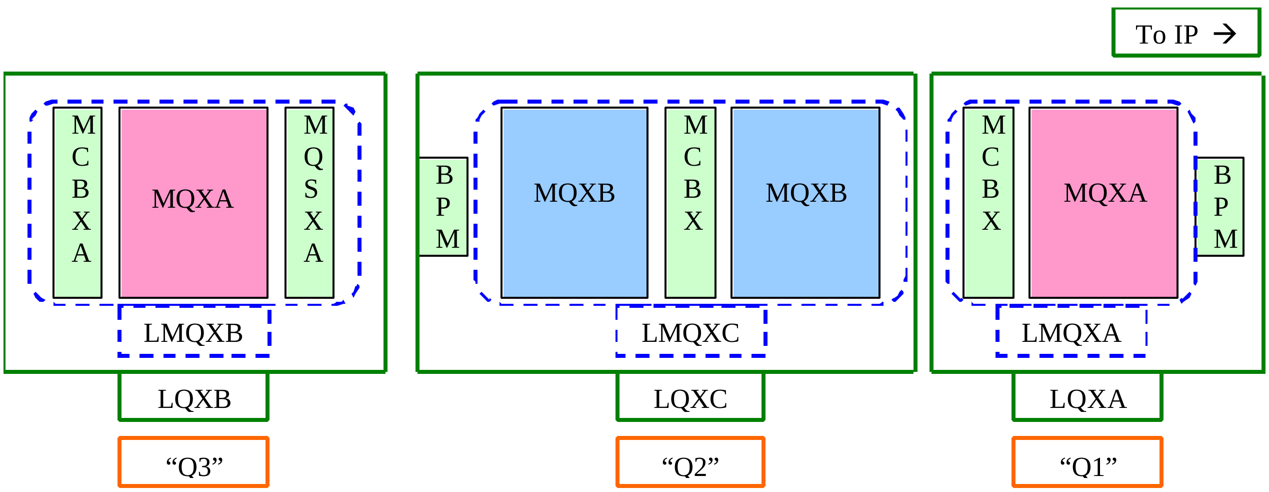

Figure 1. Inner Triplet Nomenclature.

The MQXB design (Figure 2) consists of a 2-layer Nb-Ti graded coil, which incorporates 1 wedge in each layer for field quality and which is insulated using Kapton film. G11CR material is used in the end parts. The coil package is supported in the straight section by stainless steel collars, which are locked with two keys in each quadrant. Over the ends, quadrant blocks and aluminium end cans are used to provide a level of support consistent with that seen in the body section. A two piece iron yoke provides flux return and a small amount of field augmentation. The collared coil is aligned within the yoke by four non-magnetic keys. The whole assembly is surrounded by a stainless steel skin. The skin is welded to stainless skin alignment keys, which together provide the closure of the helium vessel. The skin alignment keys are also the mechanical fiducial used in the alignment measurements. Stainless steel plates are circumferentially welded to the skin at each end of the MQXB, and provide longitudinal support to the coil ends. A detailed description of the MQXB design can be found in [2].

The main and auxiliary bus work, heater wires, quench detection and cryogenic instrumentation are routed through the cold mass in 4 rectangular slots. Four circular holes are provided in the yoke for thermal conduction during operation in the Helium II bath. The end plates provide anchor points for the end cans supporting the coils, and attachment points for the quadrant lead splice block, the MCBX corrector package, and the extensions and end domes which are attached during the LMQXC assembly process.

A total of 9 LQXC assemblies will be supplied to CERN, 8 for installation and a single spare, so that in production 18 MQXB will be made.

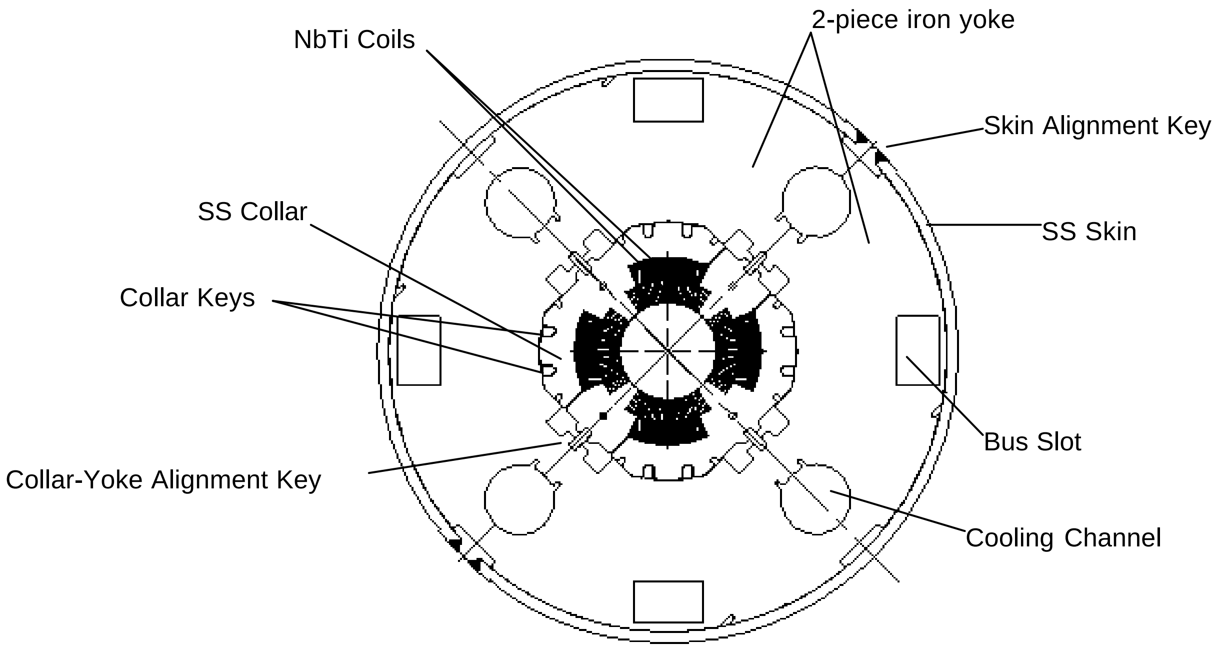

Figure 2. Cross-section through the body of the MQXB.

2. MAGNETIC REQUIREMENTS

2.1 OPERATING GRADIENT

Table 1 and 2 list operating parameters of the MQXB magnet for nominal operation in the LHC [3]. Figure 3 shows the transfer function of the MQXB as a function of excitation current. Under collision optics at nominal energy, the maximum gradient (205 T/m) is achieved at IR2 for β^* = 0.5 m. At ultimate energy, the high luminosity IRs 1 and 5 will be required to go to β^* = 0.5 m, which corresponds to a gradient of 214 T/m. The range of β^* at the low luminosity IRs 2 and 8 will be limited, as shown in Table 2, such that the gradients there will not be required to exceed the gradient at IR 1 and IR 5.

Table 1 Parameters for the MQXB Quadrupole.

Item	***Value***
Magnetic length	5.5 m
Integral field, magnet-to-magnet variation, rms	5×10^{-4}
Short sample current at 1.9K	13840 A
Short sample gradient at 1.9 K	247 T/m
Inductance	18.5 mH
Stored energy 215 T/m	1.32 MJ

Table 2 Operational β* and Gradients for the MQXB Quadrupole.

	Interaction Region		
	1, 5	***2***	***8***
Injection, E=0.45 TeV			
β* (m)	18	10	10
Gradient (T/m)	12.3	14.1	14.1
Current (kA)	0.67	0.77	0.77
Collision, E=7.00 TeV			
β* (m)	0.5	0.5 - 50	1.0 - 50
Gradient (T/m)	199	205 – 145	204 – 164
Current (kA)	11.05	11.39 – 7.99	11.33 – 9.06
Ultimate, E=7.54 TeV			
β* (m)	0.5	12 - 50	11 - 50
Gradient (T/m)	214	214 – 156	214 – 177
Current (kA)	11.91	11.91 –8.61	11.91 – 9.79

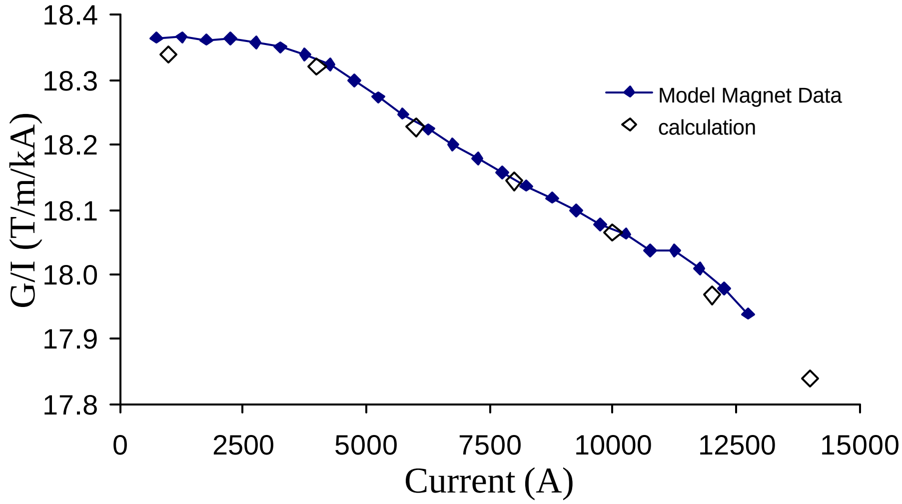

Figure 3. MQXB Transfer function.

2.2 FIELD QUALITY

The expected field quality of superconducting magnets is characterised by reference tables showing the expected mean value ($<b_n>$ or $<a_n>$), uncertainty in the mean (Δb_n or Δa_n), and rms variation about the mean ($\sigma(b_n)$ or $\sigma(a_n)$) of the field harmonics. The expected distribution of harmonics for the MQXB quadrupoles is based on the measured field quality of a series of five 2 m model magnets, whose coil geometry differs from the production MQXB magnets only in length [4].

The reference harmonics table for the MQXB quadrupole is given in Tables 3, with values presented for the magnet body at injection and collision conditions, and for the lead and the return ends. The injection harmonics correspond to 0.45 TeV beam energy and field gradient ranging from 12.3 T/m to 14.1 T/m. The error tables are unchanged over the range of injection gradients with the exception of the b_6. The collision body harmonics are unchanged over the range of required gradients shown in Table 2. The end error tables are unchanged between injection and collision conditions. The field quality given by Table 3 has been used as input for tracking studies, which have demonstrated that, with the correction system specified in [1], the required dynamic aperture is achieved under collision conditions [5].

Table 3 MQXB reference harmonics v3.2. All numbers are averaged over the respective magnetic length, and expressed in units at a reference radius of 17mm. End harmonics are the same at collision and injection energies.

MQXB Body at Injection Energy (L_{mag} = 4.76 m)

n	<b>	Δb	σ(b)	<a>	Δa	σ(a)	
2							
3	0	0.60	0.27	0	0.23	0.27	
4	0	0.15	0.27	0	0.20	0.27	
5	0	0.15	0.10	0	0.15	0.10	
6	-1.6 -1.2	0.60 0.60	0.60 0.50	0	0.07	0.20	G=12.3 T/m G=14.1 T/m
7	0	0.04	0.02	0	0.03	0.02	
8	0	0.008	0.020	0	0.008	0.020	
9	0	0.008	0.010	0	0.008	0.010	
10	0	0.008	0.010	0	0.008	0.010	

MQXB Body at Collision Energy (L_{mag} = 4.76 m)

n	<b>	Δb	σ(b)	<a>	Δa	σ(a)
2						
3	0	0.60	0.27	0	0.23	0.27
4	0	0.15	0.27	0	0.20	0.27
5	0	0.15	0.10	0	0.15	0.10
6	0	0.45	0.20	0	0.07	0.20
7	0	0.04	0.02	0	0.03	0.02
8	0	0.008	0.020	0	0.008	0.020
9	0	0.008	0.010	0	0.008	0.010
10	0	0.008	0.010	0	0.008	0.010

MQXB Lead End (L_{mag} = 0.42 m)

n	<b>	Δb	σ(b)	<a>	Δa	σ(a)
2				46.2		
3	0	0.90	0.80	0	0.90	0.80
4	0	0.70	0.80	0	0.70	0.80
5	0	0.40	0.50	0	0.40	0.50
6	3.1	0.20	0.07	-0.35	0.20	0.07
7	0	0.10	0.04	0	0.10	0.04
8	0	0.030	0.025	0	0.030	0.025
9	0	0.010	0.008	0	0.010	0.008
10	-0.05	0.010	0.005	0	0.010	0.005

MQXB Non-Lead End (L_{mag} = 0.33 m)

n	<b>	Δb	σ(b)	<a>	Δa	σ(a)
2						
3	0	0.90	0.80	0	0.90	0.80
4	0	0.70	0.80	0	0.70	0.80
5	0	0.40	0.50	0	0.40	0.50
6	-0.4	0.30	0.07	0	0.20	0.07
7	0	0.10	0.04	0	0.10	0.04
8	0	0.030	0.025	0	0.030	0.025
9	0	0.010	0.008	0	0.010	0.008
10	-0.05	0.050	0.005	0	0.010	0.005

2.3 FIELD AXIS

The allowable twist and straightness of the MQXB cold mass is shown in Table 4, and achievement of these values has been confirmed through measurements taken during the model magnet program [6]. The values are extracted from the IR Quadrupole Reference Alignment Table [7].

Table 4 Estimated field angle error tolerances.

Item	***Value***
MQXB twist	1 mrad / 5 m
MQXB straightness	100 μm / 5m

3. ELECTRICAL REQUIREMENTS

3.1 POWER LEADS AND BUSSES

The lead end orientation of all Q2a magnets (MQXB nearest the IP) is toward the interaction point, and that of all Q2b magnets (MQXB furthest from the IP) is away from the interaction point.

Each magnet is provided with a pair of power leads made of the same superconducting cable as used in the coils. Each lead will be marked “A” or “B” according to the standard LHC convention [8] such that, when facing the lead end of the magnet, with current entering the “A” lead and exiting the “B” lead, a quadrupole gradient with vertical field increasing to the left is produced.

Superconducting buswork is required for the series connection of Q2a and Q2b, and this bus is installed when the LMQXC cryoassembly is made. Additional buswork is required for connecting Q1 and Q2 leads to the external power supplies. As shown in Figure 2, there are 4 30 mm x 50 mm rectangular slots in the iron. The bottom bus slot is allocated for the high current bus. The estimated total cross section of the bus is less than 20 mm x 20 mm, which will fit comfortably within the allocated slot.

Additional bus work for correctors, carrying less than 600 amps, will be routed through one of the side bus slots.

3.2 QUENCH PROTECTION

During a quench the magnet should be limited to a peak “hot spot” temperature of =400K, and the peak voltage to ground is expected to be less than 450 V [9]. This is accomplished within the context of the CERN supplied power supplies, CERN supplied quench detection system and CERN supplied strip heater power supplies, through the use of voltage taps and quench protection strip heaters.

The magnet will have voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit. This configuration allows quenches to be detected via a voltage imbalance between half magnet coil circuits. There are four strip heaters per magnet, with each heater covering approximately 12 turns of two azimuthally adjacent outer coils. The four heaters are wired into two independent circuits. Each circuit will quench all four quadrants and provides full magnet protection.

Once a quench is detected in any element in the inner triplet, the power supply system will be turned off and all quench protection strip circuits in all magnets in the triplet will be energised.

3.3 INSTRUMENTATION

Two resistance thermometers are installed in the each cold mass, to assist in the cryogenic control of the cool-down, steady state operation, and warm-up of the magnets. Two 120W electrical heaters are located in each cold mass to assist in magnet warm-up.

For quench protection, two voltage taps will be provided at each of the two magnet leads and the centre point of the coil. Each quench heater circuit will have two leads, for a total of four. Wires will be insulated with polyimide, according to the recommendations in [10].

The rectangular bus slots, as shown in Figure 2, that are not otherwise allocated for bus work, will be used for routing instrumentation wires. Wires for the Q2 magnet as well as feed-throughs from the Q1 magnet pass through the MQXB, and include voltage taps and quench protection heaters leads and cryogenic instrumentation leads.

3.4 VOLTAGE LIMITS

All components are designed to withstand the maximum voltages that can appear during normal operation, including ramping up, ramping down and quenching. The magnet coils and the quench protection heaters will be tested in liquid helium at 1 atm pressure prior to installation in the machine, to the voltages specified in Table 5, based on the estimated peak voltages to ground [9] and on the test specifications in [11]. Prior to cryogenic operation, additional hi-pot tests will be performed in room temperature nitrogen gas to assure that the magnets meet these specifications.

Table 5 Required hi-pot test voltages in liquid helium at 1 atm pressure prior to installation in the machine.

Circuit Element	V_{max}	$V_{hi\text{-}pot}$
Quench Protection Heaters	450 V	1400 V
Magnet Coil	450 V	1400 V

4. CRYOGENIC REQUIREMENTS

All MQXB magnets operate in 1.9K superfluid helium bath. The magnets are designed for 20 bar maximum internal pressure, and are pneumatically pressure tested to 125% of that value during acceptance tests.

5. RADIATION REQUIREMENTS

The inner triplets of the LHC are subjected to extremely high radiation loads due to secondaries from the pp-interactions, particularly at the high luminosity interaction points 1 and 5. The actual dose rate depends on the location of the magnet, and varies strongly within the individual magnet in both azimuth and longitudinal position. The maximum dose rate along the LQXC in IP 1 and 5 is at 43 m from the interaction point at the coil mid-plane. Table 6 summarises the peak yearly-integrated dose expected [12] to be deposited in the G11CR inner coil end parts, which are the most radiation vulnerable components, the inner coil straight section, where the dose is maximum, and at the outer radius of the vacuum vessel for the LQXC. The peak dose rates in the coil and end parts are averaged over 20 degrees in azimuth. The annual dose is calculated based on the assumption that the LHC operates for 200 days per year at an average luminosity which is 50% of the nominal luminosity of $1x10^{34}cm^{-2}sec^{-1}$.

The material limitations are taken from [13]. The least radiation tolerant material used in the magnet is G11CR, which is used in the coil end parts and in the collet assemblies that provide mechanical support to the coil ends. The radiation lifetime of the MQXB quadrupole is expected to be limited by the end part material, whose mechanical properties are degraded by 50% after an integrated dose of approximately 20 MGy. At the dose rate given in Table 6, this corresponds to approximately 7 years radiation lifetime.

Table 6 Expected yearly radiation dose at nominal luminosity in IP1/5 as a function of radial location.

Radial Location	***Interaction Region***	***Dose, MGy/yr***
Inner coil straight section	IR1/5	3.9
Inner coil end parts	IR1/5	3.4
Vacuum Vessel	IR1/5	0.006

6. RELIABILITY REQUIREMENTS

6.1 LIFETIME

The quadrupoles are expected to survive 6 years of LHC operation under nominal luminosity conditions, limited primarily by the integrated radiation dose to the materials in the coils. To extend the useful life of the magnets beyond this, the inner triplet assemblies may be interchanged between the low luminosity and high luminosity IPs. The number of thermal cycles, powering cycles, and quenches required over the expected lifetime of the LHC machine are shown in Table 7.

Table 7 Required lifetime parameters.

Item	*Value*
Number of Thermal Cycles	25
Number of Powering Cycles	12,000
Number of Quenches	10

6.2 SPARES

A fully tested LQXC cryoassembly, containing two MQXB magnets, will be delivered to CERN as a spare. The spare will include a kit of field added parts necessary to allow it to be installed in any location.

7. CERN PROVIDED PARTS

CERN has agreed to provide several components to be installed in the MQXB quadrupole to ensure compatibility with CERN data acquisition and control systems. These are listed in Table 8. These will be provided for the planned two full-scale prototype MQXB as well as for the production magnets.

Table 8 CERN provided parts.

Item	*Quantity*
Quench Protection Heaters	84
Temperature Sensors	42
Warm-up Heaters (120 W)	42

8. LIST OF INTERFACES

All interfaces of the MQXB cold mass assembly are to other components in the LMQXC helium vessel and the LQXC cryostat. The details of these interfaces are contained in separate documents listed in Table 9.

Table 9 MQXB Interface Specifications.

Specification	*Interfaces*
MQXB to Cryostat Interface Specification	End domes Q2a-Q2b connection Support Ring
Inner Triplet Corrector Interface Specification	MCBX

9. REFERENCES

[1] LHC Engineering Specification, “Inner Triplet Systems at IR 1, 2, 5, and 8,” LHC-LQX-ES-0001.00.

[2] N. Andreev, et al., “Mechanical Design and Analysis of LHC Inner Triplet Quadrupole Magnets at Fermilab,” MT16, Ponte Vedra Beach, FL, USA, September 1999;
N. Andreev, et al., “Status of the LHC Inner Triplet Quadrupole Program at Fermilab,” 2000 Applied Superconductivity Conference, Virginia Beach, VA, USA, September 2000.

[3] O. Brüning, “Optics Solutions in IR1 and IR5 for Ring-1 and Ring-2 of the LHC Version 6.0,” LHC Project Note 187, April 1999;
O. Brüning, “Optics Solutions in IR2 for Ring-1 and Ring-2 of the LHC Version 6.0,” LHC Project Note 188, April 1998;
O. Brüning, “Optics Solutions in IR8 for Ring-1 and Ring-2 of the LHC Version 6.0,” LHC Project Note 193, June 1998.

[4] P. Schlabach, et al., “Field Quality in Fermilab-built Models of Quadrupole Magnets for the LHC Interaction Region,” 2000 Applied Superconductivity Conference, Virginia Beach, VA, USA, September 2000.

[5] J. Strait, “IR Corrector Studies,” Fermilab Technical Division note TD-00-058, 20 April 2000;
V. Ptitsyn, et al., BNL Collider-Accelerator Department note C-A/AP Note 21, in preparation.

[6] “HGQ Short Model R&D Report,” Fermilab Technical Division note TD-00-060, Sept. 2000, A. Zlobin, ed.

[7] IR Quadrupole Reference Alignment Table, http://www-ap.fnal.gov/lhc/meetings/workshop99.html.

[8] LHC Engineering Specification, “LHC Magnet Polarities,” LHC-DC-ES-0001.00 rev 1.1, 27 April 1999.

[9] L. Chiesa and M. Lamm, “Estimation of the Peak Voltage to Ground for MQXB Under Normal Operating Condition,” Fermilab Technical Division note TD-00-050, Aug, 2000.

[10] LHC Engineering Specification, “Instrumentation Wires, Connection Techniques and Feedthroughs for the Main Arc Cryomagnets and the QRL,” LHC-QI-ES-00001 rev. 1.1, 31 Aug 2000.

[11] LHC Engineering Specification, “Voltage Withstand Levels for Electrical Insulation Tests on Components and Bus Bar Cross Sections for the Different LHC Machine Circuits,” LHC-PM-ES-001.00 rev. 1.0 17 May 1999.

[12] N. Mokhov, private communication.

[13] I. S. Baishev, A.I. Drozhdin, and N.V. Mokhov, “Beam Loss and Radiation Effects in the SSC Lattice Elements,” SSCL-306, November 1990;
H. Schönbacher et al, “Results of Radiation Tests at Cryogenic Temperature on Some Selected Organic Materials for the LHC,” CERN 96-05.